Neutrinos: The Next Steps

- How we got here: four early steps
- Particle, antiparticle, and neutrino mass
- New things we know and why we were lucky
- Open questions and challenging next steps

Four early steps

- Chadwick finds in his 1914 study that the spectrum of electrons from the β decay of ^{214}Bi is continuous
  - energy quantization, line electrons from IC were known
  - expected to see electrons carrying off the decay energy
  - suggested that some unobserved radiation accompanied the decay
  - Rutherford, Hahn, Meitner, others: perhaps a consequence of energy loss in target

1927: Ellis and Wooster observe the β decay of ^{210}Bi in a thick target, and from calorimetry determine that the energy deposited/per event, 0.34 ± 0.04 MeV, was less than the Q value, 1.05 MeV

Liebe Radioaktive Damen und Herren.....

- In 1930 Pauli hypothesized that an emission of an unobserved neutral, spin-1/2 "neutron" accounted for the apparent anomaly -- a new particle with mass < 1% that of the proton, the ν

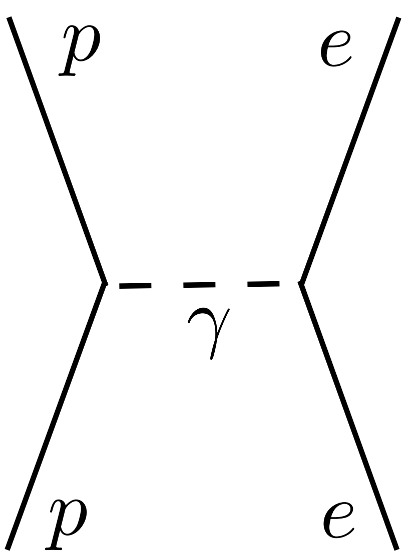
  Viewed the neutron/neutrino as a nuclear constituent, knocked out in β decay, accounting for the integral spin of the 3p nucleus ^6Li

Pauli's first public lecture on the ν was not until the 7th Solvay Conference of 1933

"I have done a terrible thing. I have postulated a particle that cannot be detected."

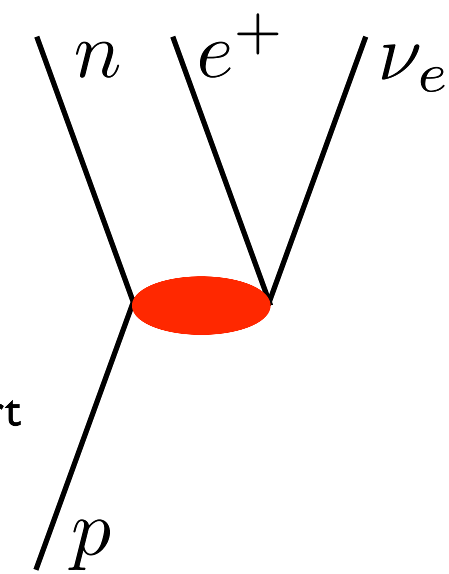
- Following Chadwick's 1932 discovery of (today's) neutron, Fermi proposed a model for decay, assuming a vector charge operator as in electromagnetism, but replacing the electric field by a contact interaction in which the four fermions couple at a point

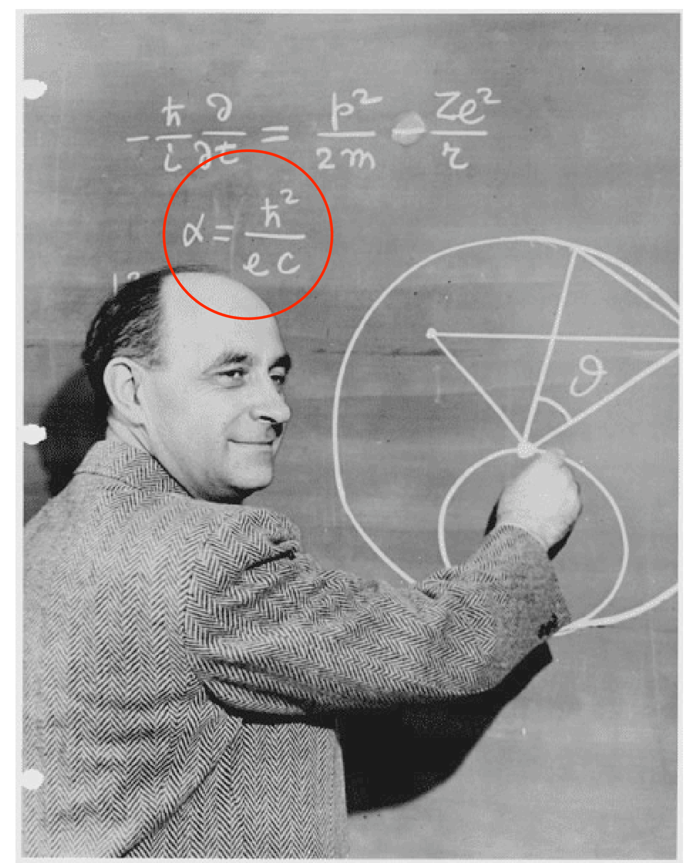
Apart from PNC, this is the standard model's low-energy limit



electromagnetic analog

current-current but no counterpart to electric field





- 1936 demonstration by Gamow and Teller that β decay required an axial coupling comparable in strength to Fermi's vector coupling

	$\mu = 0$	$\mu = 1, 2, 3$
$J_\mu^V(x)$	$\boxed{1}$	$\vec{p}/M$

Selection Rules for the β-Disintegration

G. Gamow and E. Teller, *George Washington University, Washington D. C.*

(Received March 28, 1936)

§1. The selection rules for β-transformations are stated on the basis of the neutrino theory outlined by Fermi. If it is assumed that the spins of the heavy particles have a direct effect on the disintegration these rules are modified. §2. It is shown that whereas the original selection rules of Fermi lead to difficulties if one tries to assign spins to the members of the thorium family the modified selection rules are in agreement with the available experimental evidence.

	$\mu = 0$	$\mu = 1, 2, 3$
$J_\mu^V(x)$	1	$\vec{p}/M$
$J_\mu^A(x)$	$g_A \vec{\sigma} \cdot \vec{p}/M$	$\boxed{g_A \vec{\sigma}}$

$\Delta J = 0, \pm 1$ (no $0 \leftrightarrow 0$) $\Delta\pi = 0$, e.g., $0^+ \rightarrow 1^+$ decays

This implied the correct allowed rate in the absence of polarization

$$\omega \sim |\langle 1 \rangle|^2 + g_A^2 |\langle \vec{\sigma} \rangle|^2$$

a result one can get either by

- squaring the currents separately and adding
- adding the currents and then squaring

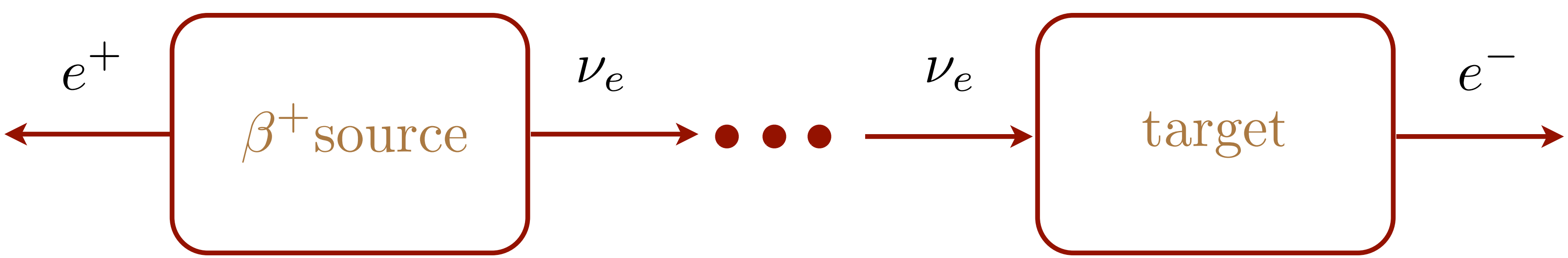
the second choice implies PNC, which they must have recognized, but did not comment on

Particles, Antiparticles, and Neutrino Mass

- particles/antiparticles: electron, positron carry opposite electric charge

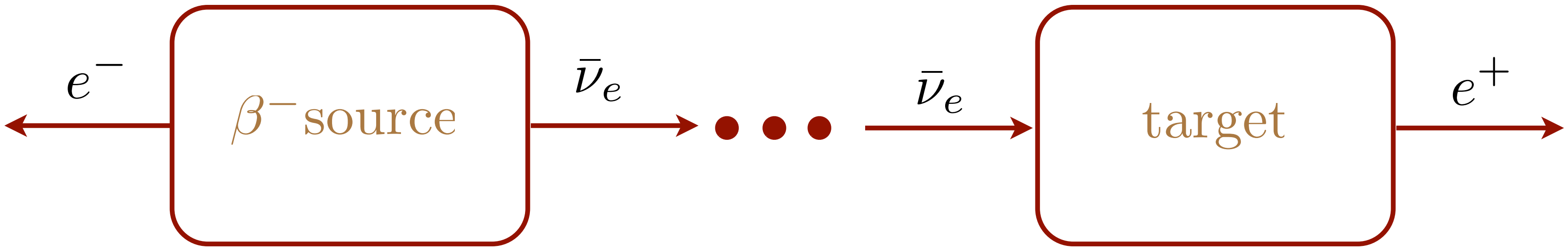
- the ν has no charge or other distinguishing additive quantum numbers, raising the question -- are the νs produced in β^- and β^+ decay the same?

so we do an experiment:



this defines the ν_e which is then found to produce: e^-

and a second one:



this defines the $\bar{\nu}_e$

which is then found to produce: e^+

- with these definitions of the ν_e and $\bar{\nu}_e$, they appear operationally distinct, producing different final states

- introduce a "charge" l_e to distinguish the neutrino states and to define the allowed reactions, by requiring l_e to be additively conserved

$$\sum_{in} l_e = \sum_{out} l_e$$

$lepton$	l_e
e^-	$+1$
e^+	-1
ν_e	$+1$
$\bar{\nu}_e$	-1

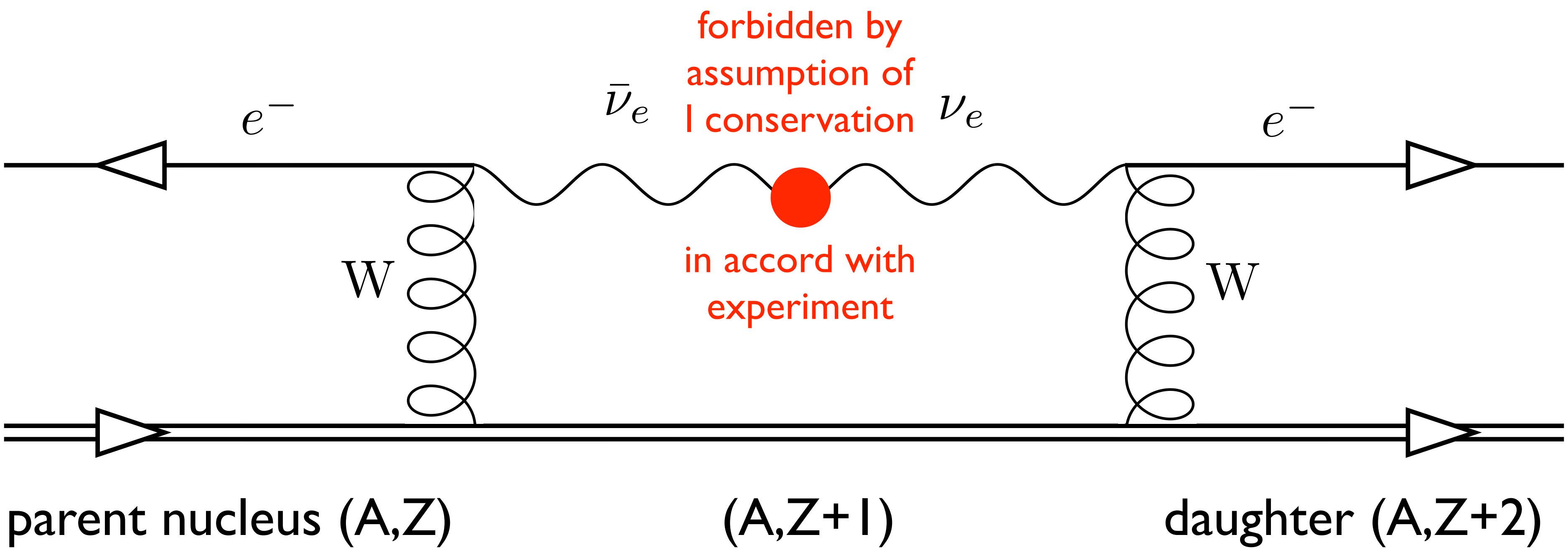
- historically connected with the development of the Cl solar neutrino detector -- Alvarez was interested in using Cl to test lepton number conservation

- Ray Davis used the Savannah River reactor to search for

$$^{37}\mathrm{Cl} + \bar{\nu}_e \to {}^{37}\mathrm{Ar} + e^-$$

but found no Ar, indicating that the ν_e and $\bar{\nu}_e$ are distinct at $\sim 5\%$

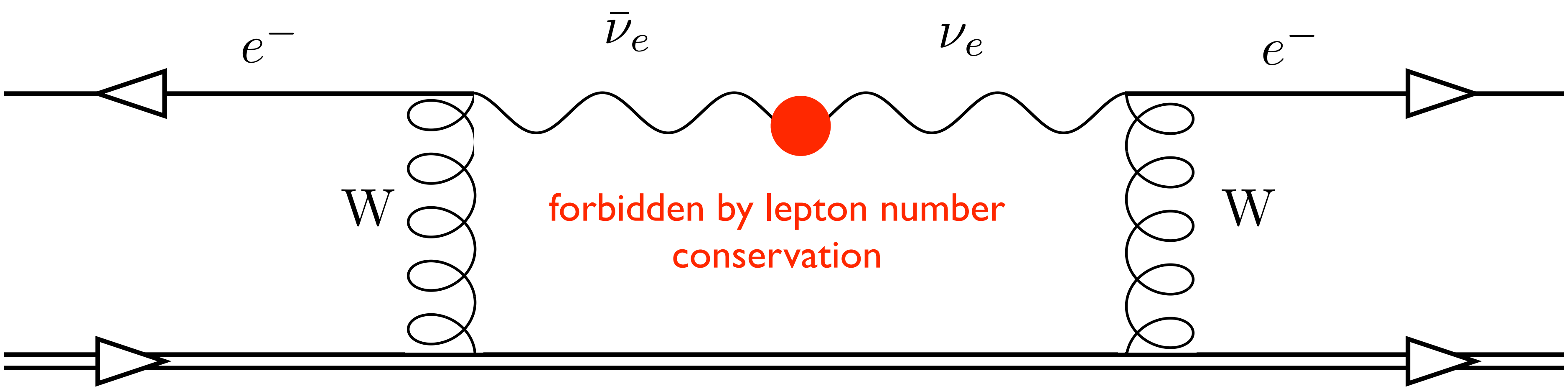
This experiment is done - the nucleus is both source and target - in neutrinoless $\beta\beta$ decay



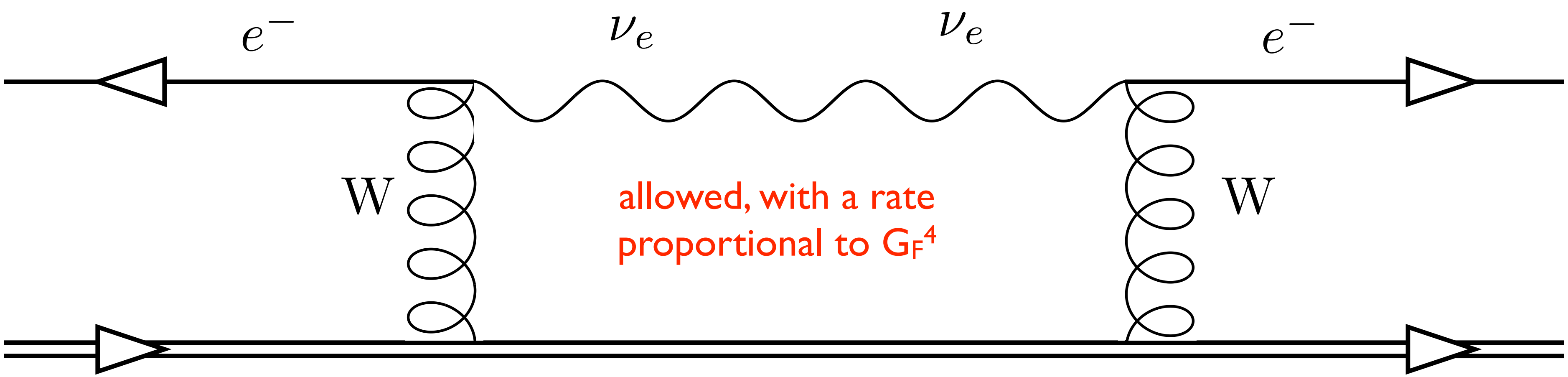
By the early 1950s it was known that neutrinoless rates were slow, leading to a prejudice that the neutrino is a Dirac particle, $\nu_e \neq \bar{\nu}_e$

The conclusion was premature, as it did not anticipate the discover of parity violation in the weak interaction in 1957

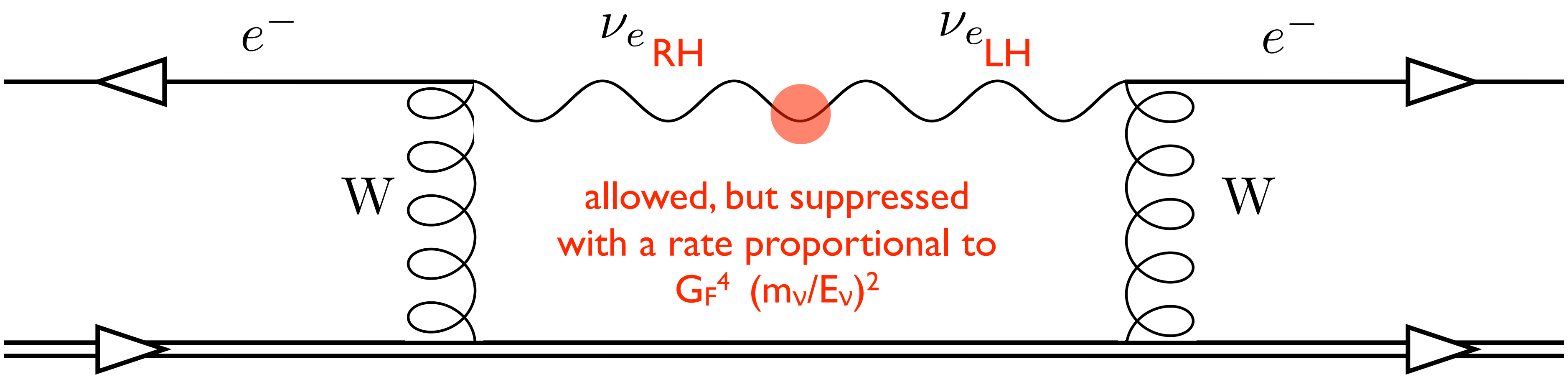
If the weak interaction produces left-handed νs and right-handed ν̅s, let's re-examine



Remove the restriction of an additively conserved lepton number



and account for suppressed rates by the nearly exact handedness

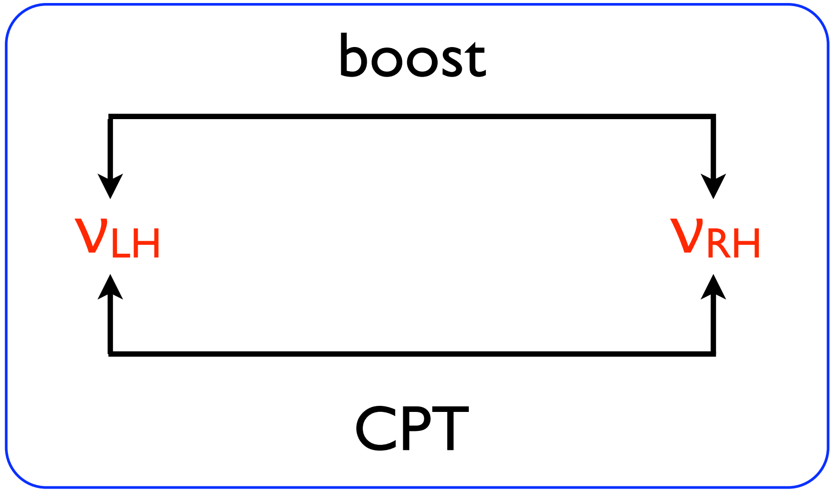


The γ_5-invariance is not exact if the ν has a mass as the "RH-ed" ν state with then contain a small piece of LH-ed helicity proportional to m_ν/E_ν where $E_\nu \sim 1/R_{nuclear}$

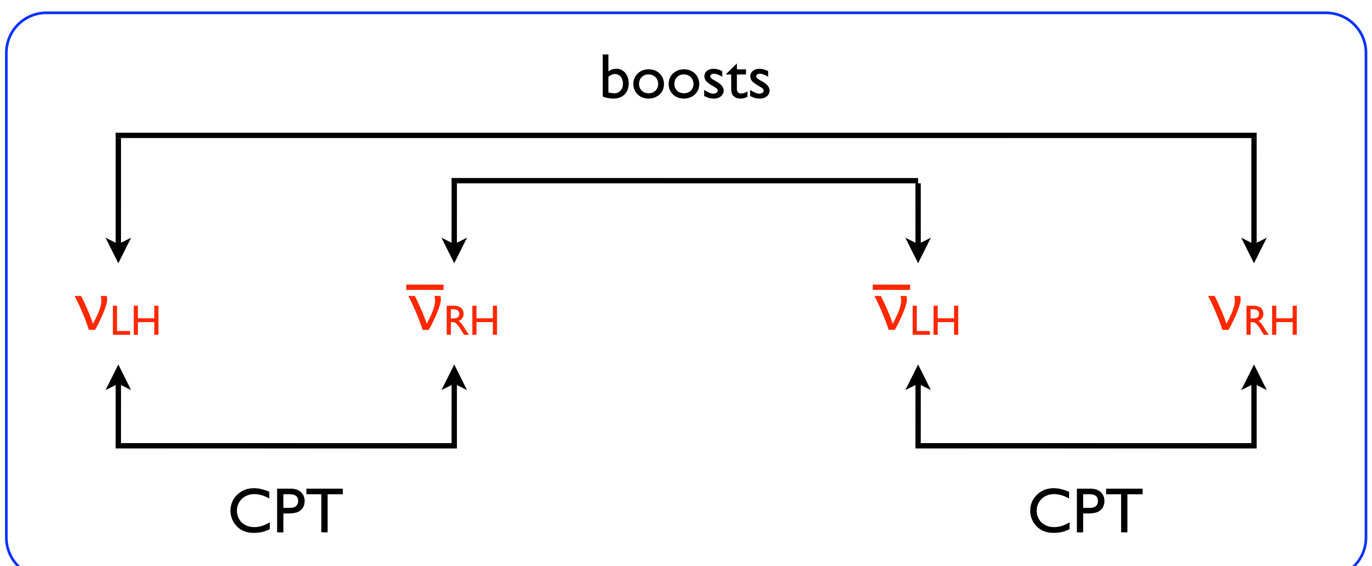
Because of PNC, there is no need for an additively conserved quantum number constraining descriptions of the ν mass: there is more freedom

Massive neutrino descriptions

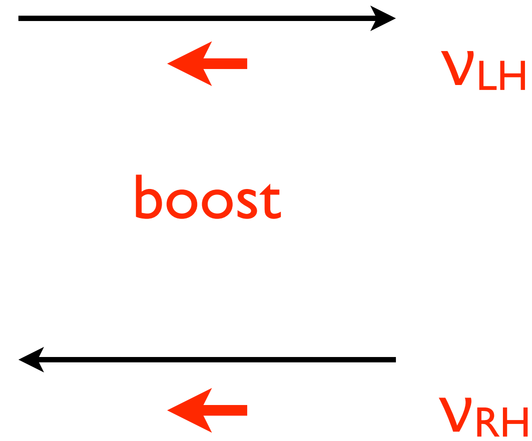
Majorana:



Dirac:



Lorentz invariance



or some linear combinations of the two

Let's see the mass consequences: start with the Dirac eq., project out

$$\psi_{R/L} = \tfrac{1}{2}(1 \pm \gamma_5)\psi] \qquad\qquad C\ \psi_{R/L}\ C^{-1} = \psi^c_{R/L}$$

Allow for flavor mixing

$$L_m(x) \sim m_D \bar{\psi}(x)\psi(x) \Rightarrow M_D \bar{\Psi}(x)\Psi(x) \qquad\qquad \Psi_L \equiv \begin{pmatrix} \Psi^e_L \\ \Psi^\mu_L \\ \Psi^\tau_L \end{pmatrix}$$

To give the mass 4n by 4n matrix

$$(\bar{\Psi}^c_L, \bar{\Psi}_R, \bar{\Psi}_L, \bar{\Psi}^c_R) \begin{pmatrix} 0 & 0 & & M_D^T \\ 0 & 0 & M_D & \\ & M_D^\dagger & 0 & 0 \\ M_D^* & & 0 & 0 \end{pmatrix} \begin{pmatrix} \Psi^c_L \\ \Psi_R \\ \Psi_L \\ \Psi^c_R \end{pmatrix}$$

Observe that the handedness allows an additional generalization

$$L_m(x) \Rightarrow M_D \bar{\Psi}(x)\Psi(x) + (\bar{\Psi}_L^c(x) M_L \Psi_L(x) + \bar{\Psi}_R^c(x) M_R \Psi_R(x) + h.c.)$$

to give the more general matrix

$$(\bar{\Psi}_L^c, \bar{\Psi}_R, \bar{\Psi}_L, \bar{\Psi}_R^c) \begin{pmatrix} 0 & 0 & M_L & M_D^T \\ 0 & 0 & M_D & M_R^\dagger \\ M_L^\dagger & M_D^\dagger & 0 & 0 \\ M_D^* & M_R & 0 & 0 \end{pmatrix} \begin{pmatrix} \Psi_L^c \\ \Psi_R \\ \Psi_L \\ \Psi_R^c \end{pmatrix}$$

which has a number of interesting properties

- the eigenvectors are two-component Majorana spinors: 2n of these
- the introduction of M_L, M_R breaks the global invariance $\Psi \rightarrow e^{i\alpha}\Psi$ associated with a conserved lepton number

- the removal of M_L, M_R makes the eigenvalues pairwise degenerate: two two-component spinors of opposite CP can be patched together to form one four-component Dirac spinor -- so one gets n of these

- the standard model lacks a ν mass, but the reasons are not fundamental
  - it has no RHed ν field, so no Dirac mass can be formed
  - to generate the proper weak isospin,

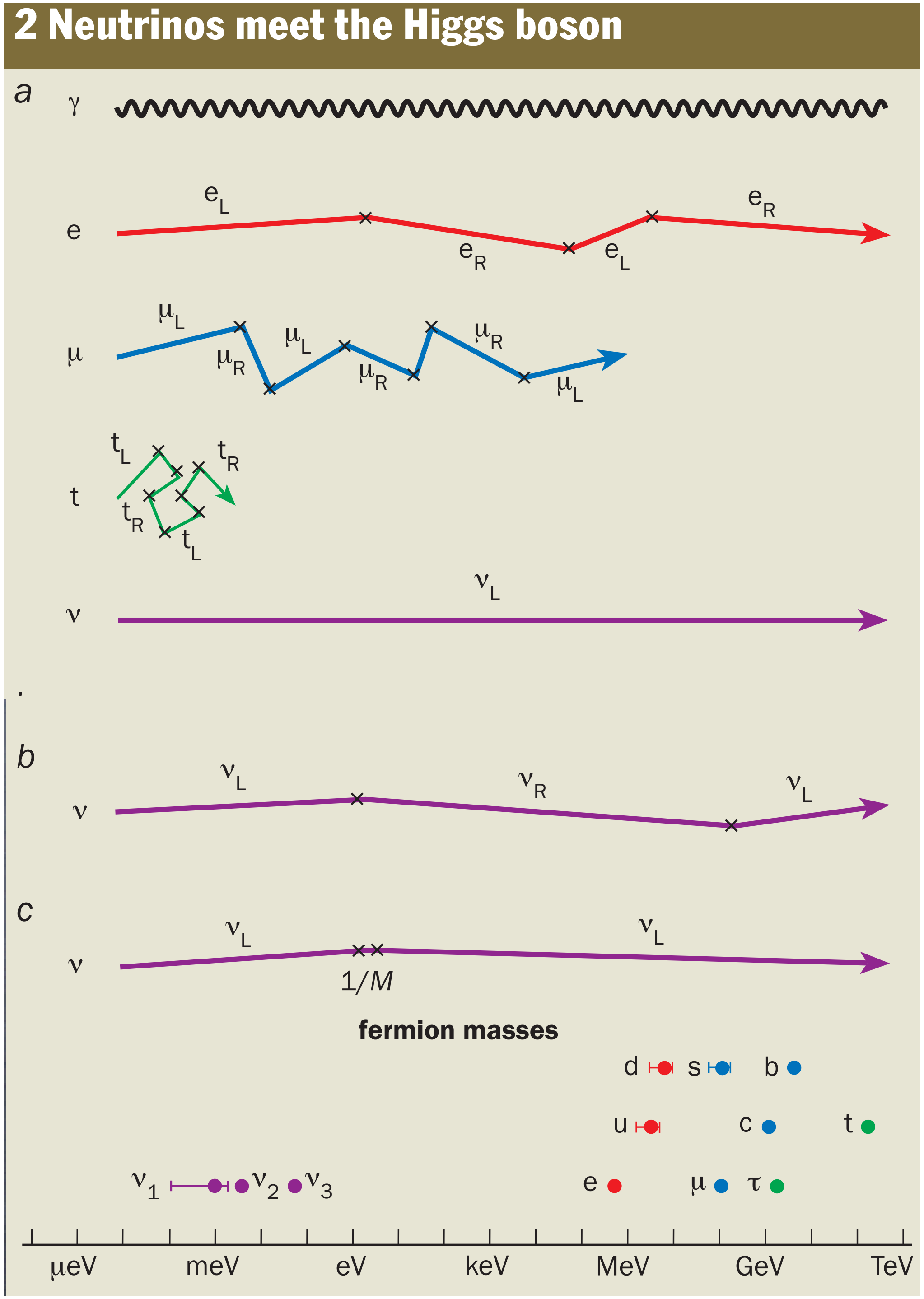
$$M_L \sim \frac{\langle \phi \rangle^2}{M_{new}}$$

    But today we regard the SM as an effective theory -- as the only dimension-five operator in the SM, ν mass is a "canary" in the SM mine indicating new physics

- most important, a natural explanation for anomalously light ν masses

$$\begin{pmatrix} M_L \sim 0 & M_D \\ M_D^\dagger & M_R \end{pmatrix} \rightarrow m_\nu^{\text{light}} \sim M_D \left(\frac{M_D}{M_R} \right) \longleftarrow$$ the needed small parameter

Hitoshi's ν mass cartoon



standard model masses

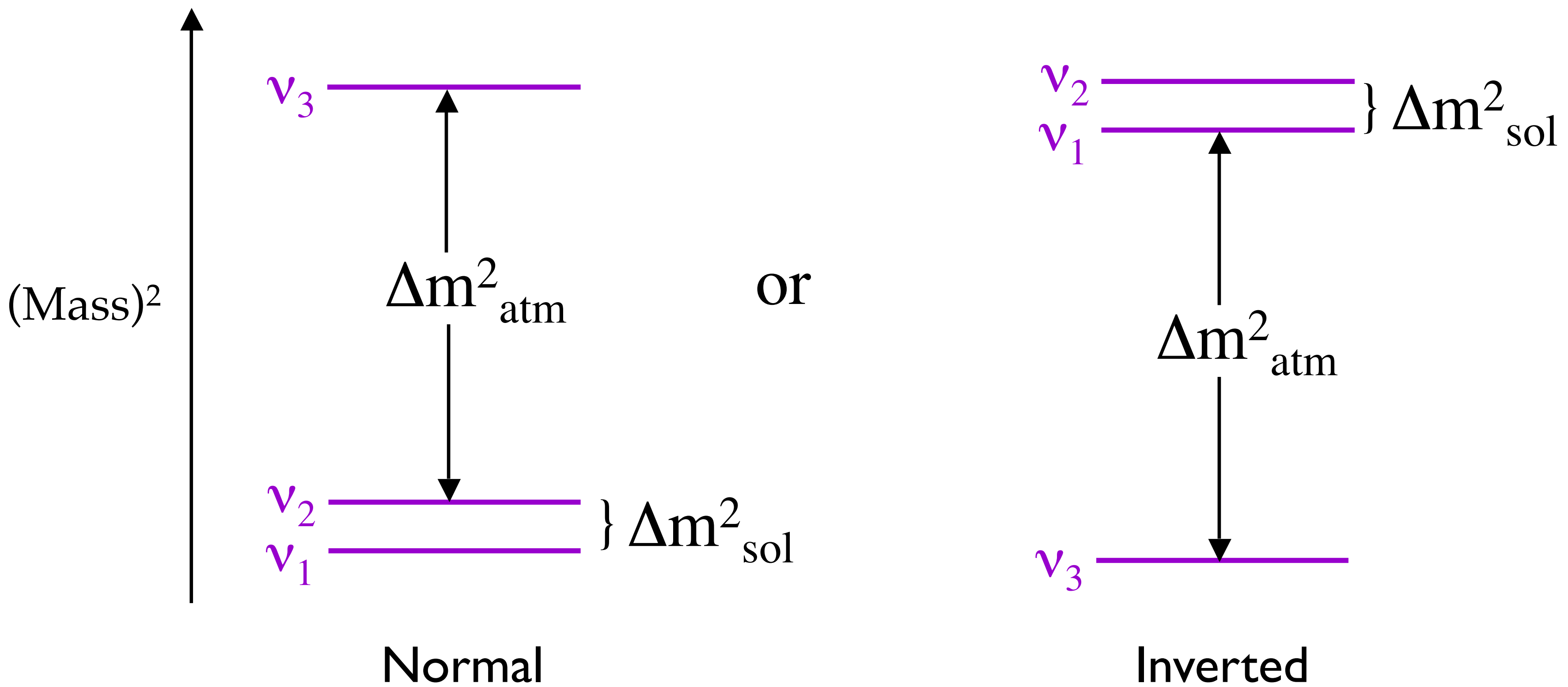
light Dirac neutrino

LHed Majorana neutrino

← the anomalous ν mass scale

New things we now know and how we were lucky

- We have seen solar and atmospheric neutrino oscillations, and determined matter effects on the former



- We were fortunate with solar νs: the earth-sun distance defines a sensitivity to $\Delta m^2 \leq 10^{-12}\ \mathrm{eV}^2$ where for most of this range the effective oscillation would be

$$1 - \frac{1}{2}\sin^2 2\theta_{12}$$

But νs require an effective mass in matter, with distinctive effects arising when the effective mass ~ the vacuum mass difference

$$\rho_{\mathrm{res}} \sim 1.3 \times 10^6 \left(\frac{\Delta m^2}{\mathrm{eV}^2}\right)\left(\frac{5\ \mathrm{MeV}}{E_\nu}\right)\left(\frac{0.5}{Y_e}\right)\cos 2\theta\ \mathrm{g/cm}^3$$

Nature chose a value, $\delta m^2_{12} \sim 8 \times 10^{-5}\mathrm{eV}^2$, where

$$\rho_{\mathrm{res}}(E_\nu \sim 10\ \mathrm{MeV}) \sim 25\ \mathrm{g/cm}^3 < \rho_{\mathrm{core}}$$

but

$$\rho_{\mathrm{res}}(E_\nu \sim 1\ \mathrm{MeV}) \sim 250\ \mathrm{g/cm}^3 > \rho_{\mathrm{core}}$$

So we were able to probe the crossing density using the solar ν spectrum, see distinctive hints of new physics, and eventually determine the mass splitting Δm_{12}

- We were also fortunate with atmospheric neutrinos. The oscillation length is

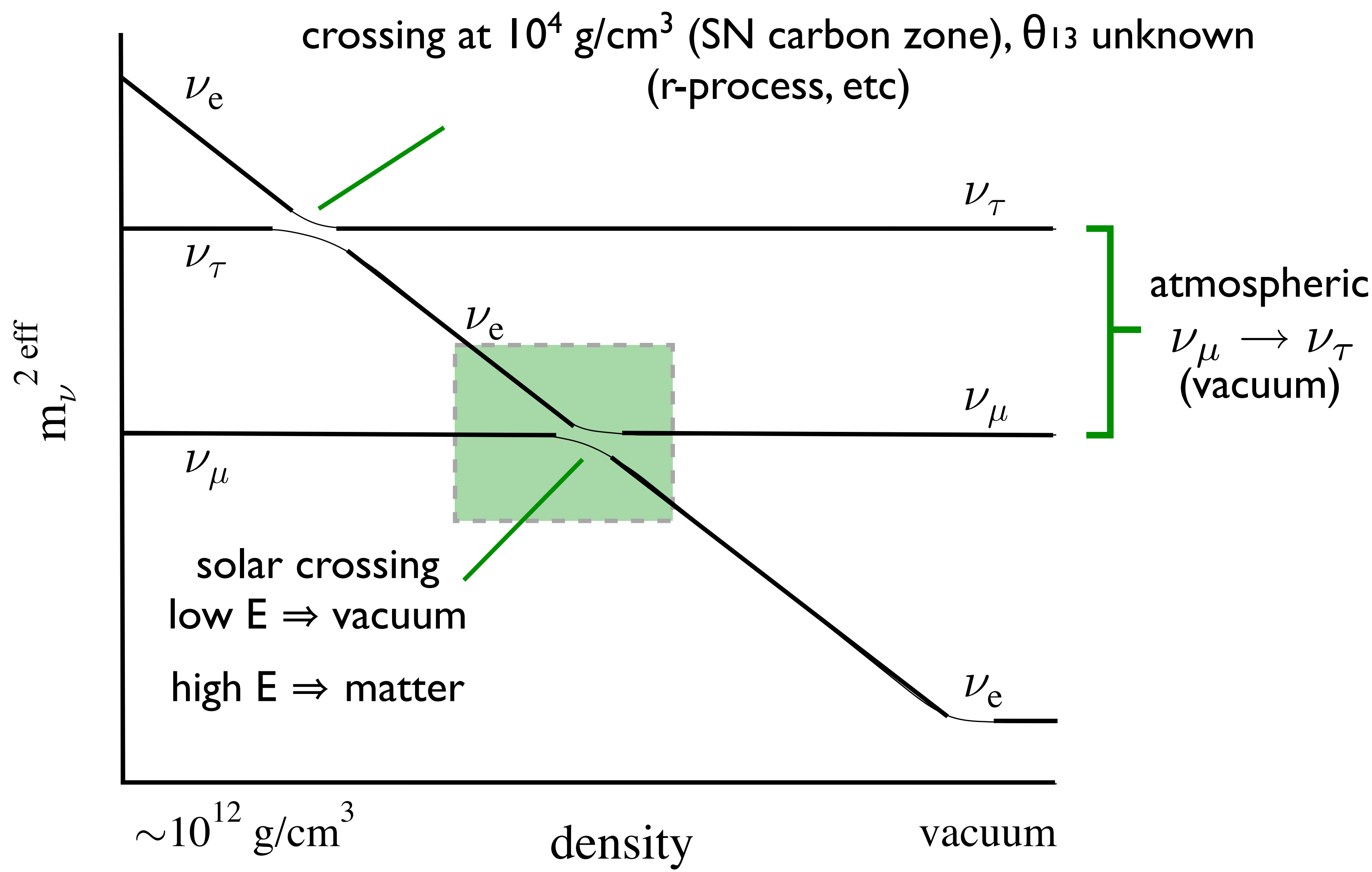
$$L_0 = \frac{4\pi\ \hbar c\ E}{\Delta m_{23}^2 c^4} \Rightarrow$$

$$\frac{L_0}{1000\ \mathrm{km}} = 1.03 \left(\frac{2.4 \cdot 10^{-3}\ \mathrm{eV}^2}{\Delta m_{23} c^4} \right) \left(\frac{E}{1\ \mathrm{GeV}} \right)$$

so nature picked a mass scale that would allow us to see unoscillated cosmic ray νs from above, and oscillated ones from below, over the key 1-10 GeV atmospheric neutrino range

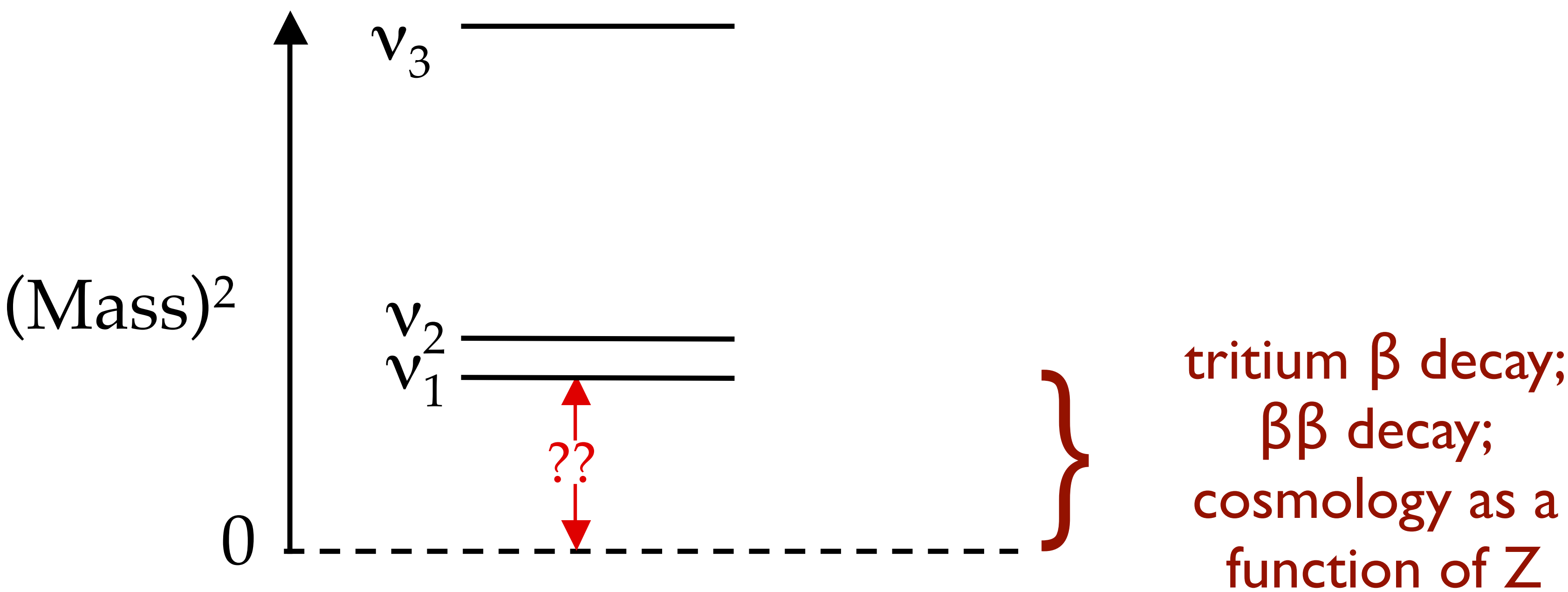
and while we have not seen matter effects (and thus do not know the sign of Δm_{23}) ...

matter effects will alter the fluxes from the next galactic supernova



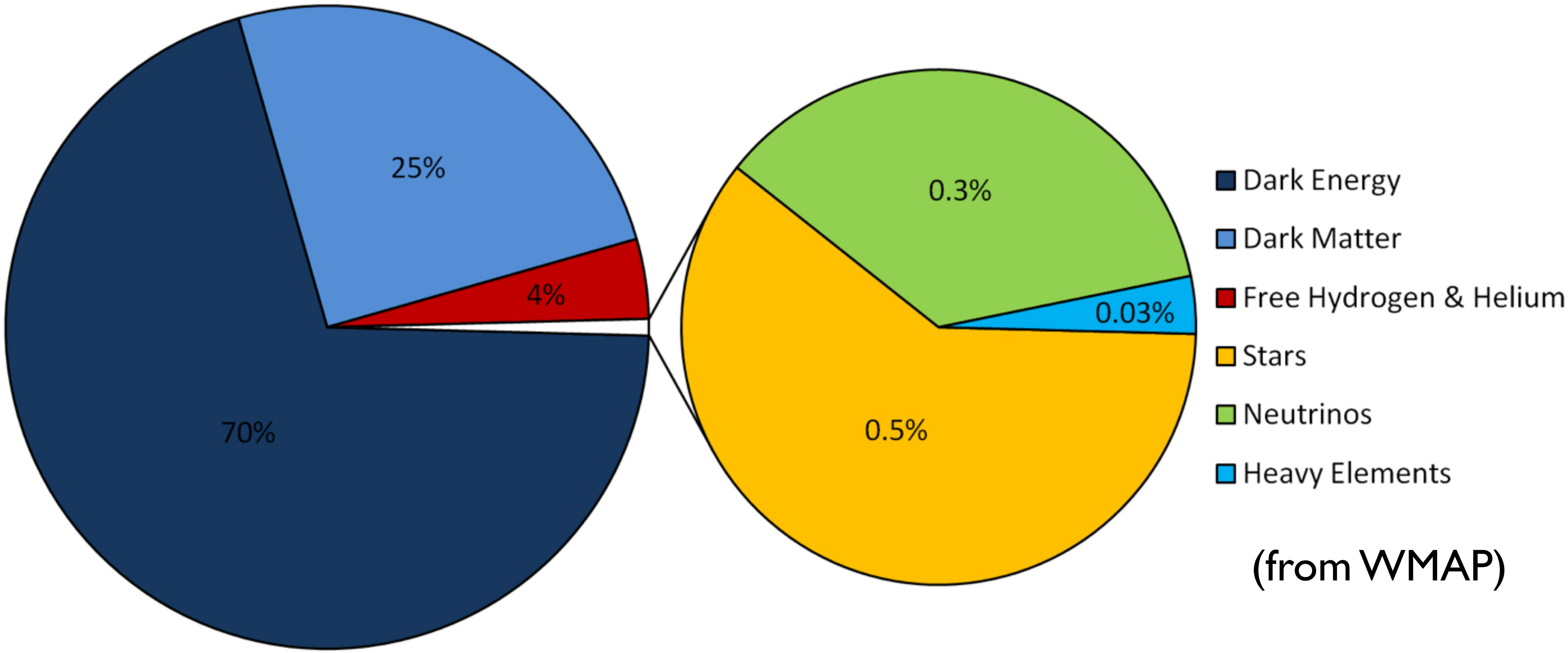
unless the third mixing angle θ_{13} is very small, < 10^{-4}

- We also had some luck with the absolute mass scale



$$50\ \text{meV} \sim \sqrt{\Delta m^2_{\text{at}}} < \sum m_i < \begin{cases} 6.6\ \text{eV}\ \ (\text{tritium}) \\ (0.2-1.0)\ \text{eV}\ \ (\text{cosmology}) \end{cases}$$

it is big enough to be measurable, potentially, but small enough that it leaves plenty of nonSM dark matter to be discovered



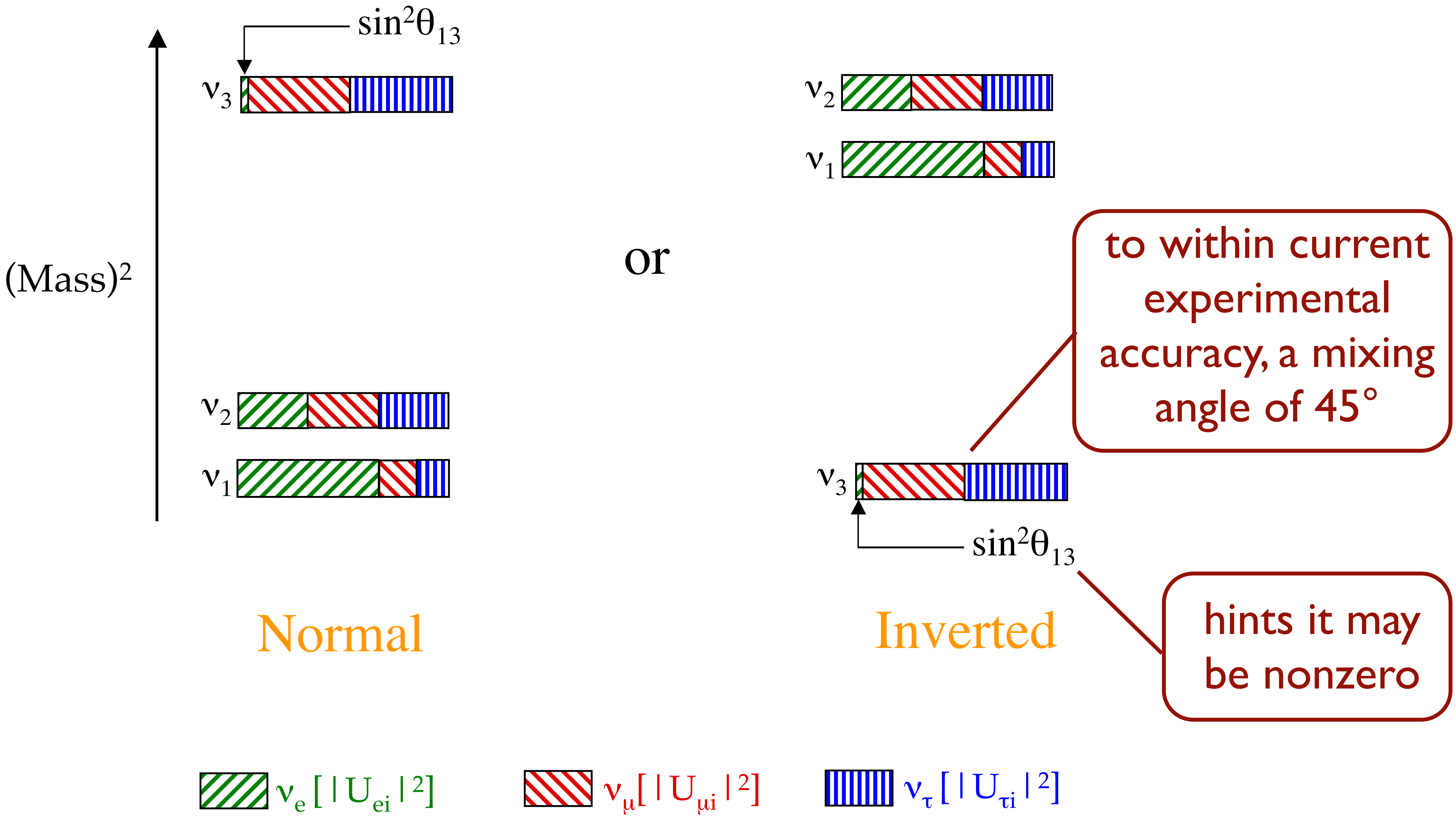
(from WMAP)

$$\rho_\nu \sim 0.011 \frac{\rho_{\mathrm{crit}}}{h^2} \sum_i m_\nu(i) \Rightarrow 0.0011 < \frac{\rho_\nu}{\rho_{\mathrm{crit}}} < 0.026$$

the optimist would point out: as this problem gets harder (one or two of the three νs with $m_\nu \sim 0$) , it also gets more interesting

$$\min \left[\sum_i m_\nu(i) \right] \sim \left\{ \begin{array}{ll} \sqrt{\Delta m_{\mathrm{at}}} & \mathrm{normal} \\ 2\sqrt{\Delta m_{\mathrm{at}}} & \mathrm{inverted} \end{array} \right.$$

- Finally, we have the hint of something quite profound



(artwork: Boris Kayser)

- One would like to understand why ν mass states correspond to highly-mixed flavor states, as this is not the pattern seen among the quarks

- Such large angles are one of the requirements for significant CP violation among νs

Open questions and challenging next steps

Neutrino mixing status: (assuming just three neutrinos)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} \nu_1 \\ e^{i\phi_1}\nu_2 \\ e^{i\phi_2}\nu_3 \end{pmatrix}$$

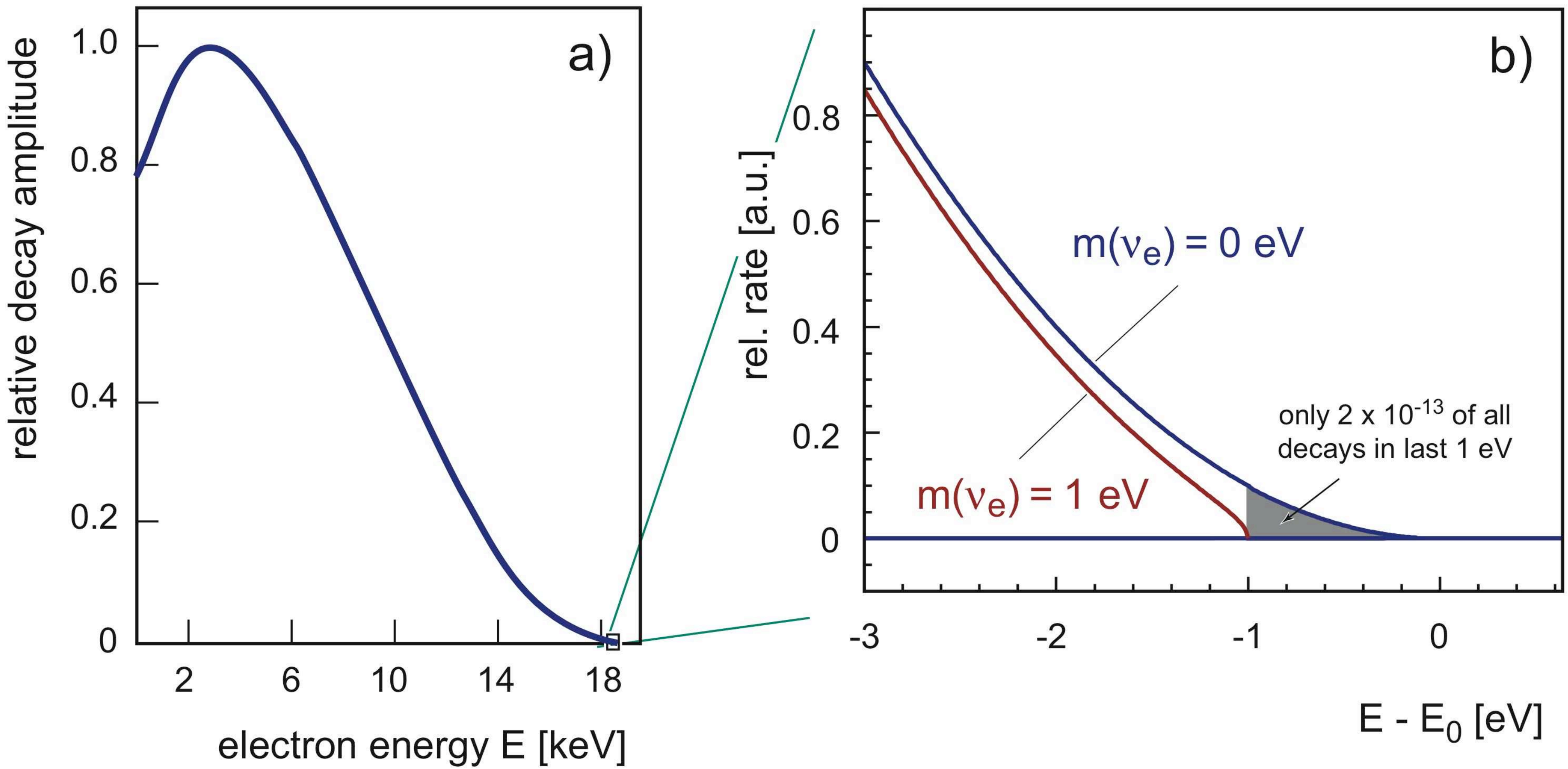
$$= \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & \boxed{s_{13}}e^{\boxed{-i\delta}} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \boxed{e^{i\phi_1}}\nu_2 \\ \boxed{e^{i\phi_2}}\nu_3 \end{pmatrix}$$

atmospheric | ν_e disappearance | solar

results: $\theta_{23} \sim 45^\circ$ | $\sin\theta_{13} \leq 0.17$ | $\theta_{12} \sim 30^\circ$

Δ_{12} | $|\Delta_{23}|$ | $\boxed{\text{sign}[\Delta_{23}]}$ | $\boxed{\text{absolute scale}}$

❑ the absolute mass



1) tritium β decay $\langle m_\nu \rangle_{\text{tritium}} = \sum_i |U_{ei}|^2 m_\nu^2(i)$

present limit $\langle m_\nu \rangle_{\text{tritium}} < 2.2\ \text{eV}$ Mainz & Troitzk

KATRIN's goal is to reach 250 meV, with 5σ exclusion at 350 meV

2) less direct, but with more potential reach: neutrinoless ββ decay

$$\langle m_\nu^{\rm Maj} \rangle = \sum_{i=1}^{2n} \lambda_i U_{ei}^2 m_i \quad \text{or} \quad \langle \frac{1}{m_\nu^{\rm heavy}} \rangle = U_{ei}^2 \frac{1}{m_i^{\rm heavy}}$$

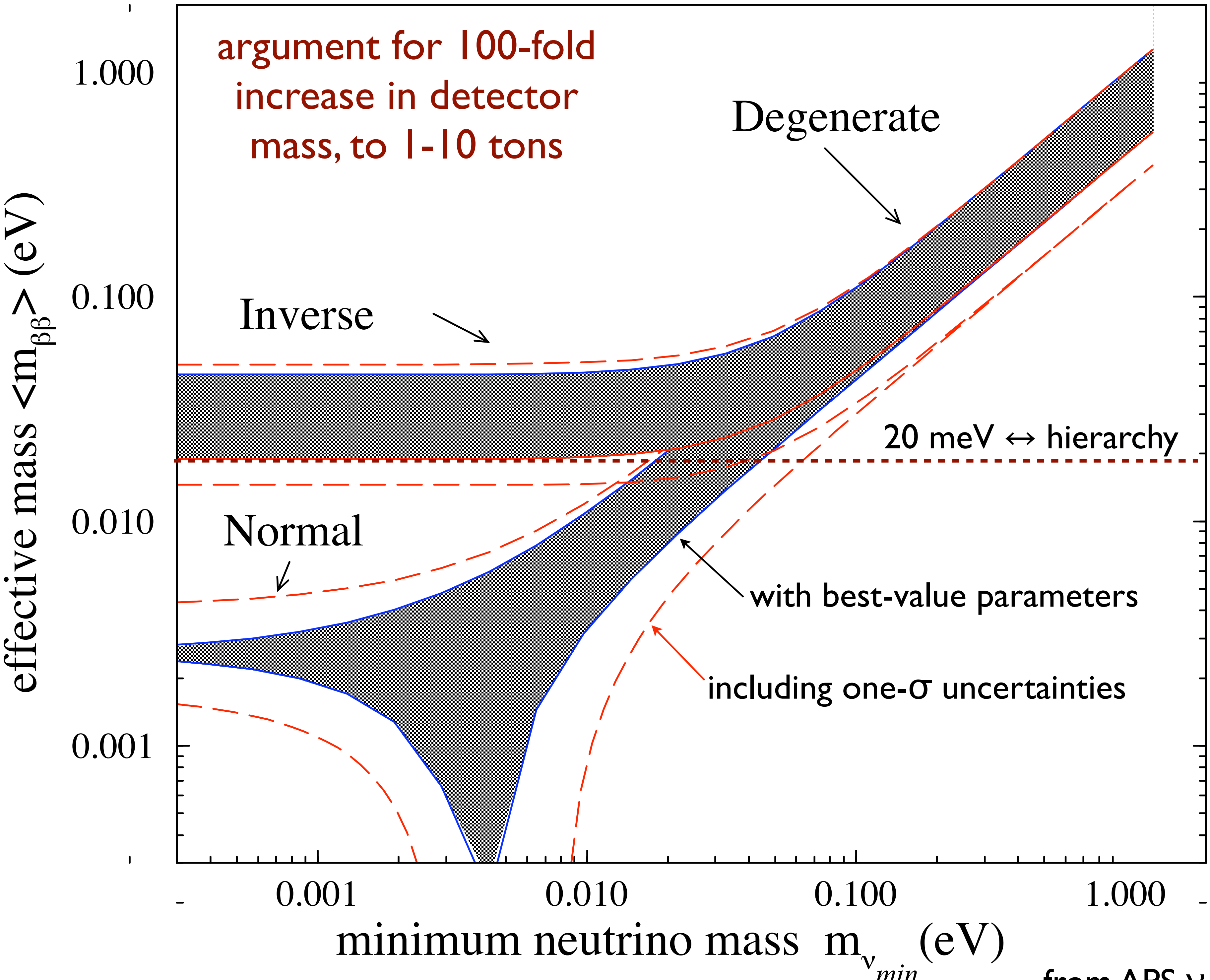
unique as a test for total lepton number violation:
observation requires Majorana masses (or extreme fine tuning)

GERDA, CUORE currently limit

$$\langle m_\nu^{\rm Maj} \rangle < (0.3 - 1.0) \ {\rm eV} \qquad \langle \frac{1}{m^{\rm heavy}} \rangle < \frac{1}{10^4 \ {\rm TeV}}$$

but
- measures only Majorana masses
- even if CP is conserved, may measure mass differences as $\lambda_i = \pm 1$ is the relative CP of the mass eigenstates
- and with CP violation, is affected by two Majorana phases that are otherwise unmeasurable

it helps that we now know something about the U_{ei}^2



from APS ν Study

3) but the best hope may be cosmology

- To "measure" ν mass cosmologically at $\sqrt{\Delta m_\nu^{2\ \mathrm{atmos}}}$, need a sensitivity to hot dark matter at ~ .001 ρ_{crit} : current sensitivity ~ .013 ρ_{crit}

- physics: νs with a smaller mass remain relativistic longer, travel further, and suppress growth of structure on larger scales

- thus one can look for a cosmological *change* with Z; at fixed Z, the changes are scale dependent:
  this is the source of the sensitivity $k_{\mathrm{free\ streaming}} \sim 0.004\sqrt{m_\nu/0.05\mathrm{eV}}\ \mathrm{Mpc}^{-1}$

$$\sum m_\nu \sim 0.05\ \mathrm{eV},\ \ z = \begin{pmatrix} 3.5 \\ 3.5 \\ 1.5 \\ 0.0 \end{pmatrix} \Rightarrow \text{power decrease} \sim \begin{pmatrix} 1.9\% \\ 1.0\% \\ 2.1\% \\ 3.5\% \end{pmatrix} \text{ for } k > \begin{pmatrix} 0.6 \\ 0.03 \\ 0.6 \\ 0.6 \end{pmatrix} \frac{1}{\mathrm{Mpc}}$$

the neutrinos are effective in altering the evolution of matter+CDM at the few % level, even though they comprise only 0.1% of today's energy density

- the precision of LSS surveys scales $\propto 1/\sqrt{N}$, so a factor of 100 needed

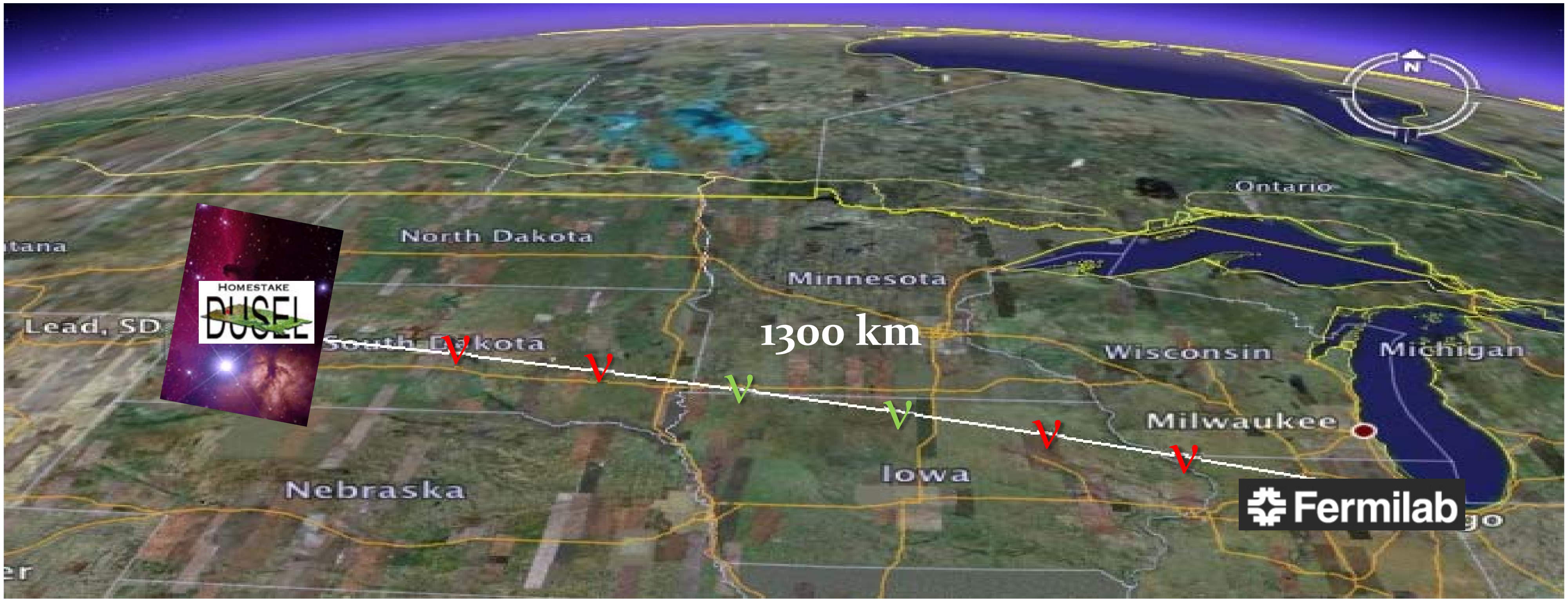
- effects that are scale-dependent at fixed Z, and evolve in a characteristic way with Z, and that can be differentiated from other parameter changes

- good news: there are a variety of both high-Z and low-Z surveys in preparation that envision such enlarged data sets
  - various analyses of combined projected data sets (high-redshift galaxy surveys, SDSS-III BOSS 10^5 QSO survey, Planck CMB data, 21cm radio telescopes with 0.1 km^2 collection, weak lensing ...) sensitive to $m_\nu \sim 50$ meV at $1 - 7\sigma$

- but will the non-cosmologists believe an analysis that combines different data sets sensitive to different scales, to determine a particle-physics parameter?

systematics will dominate: will the various data sets that sample in Z and scale yield a consistent picture when combined?

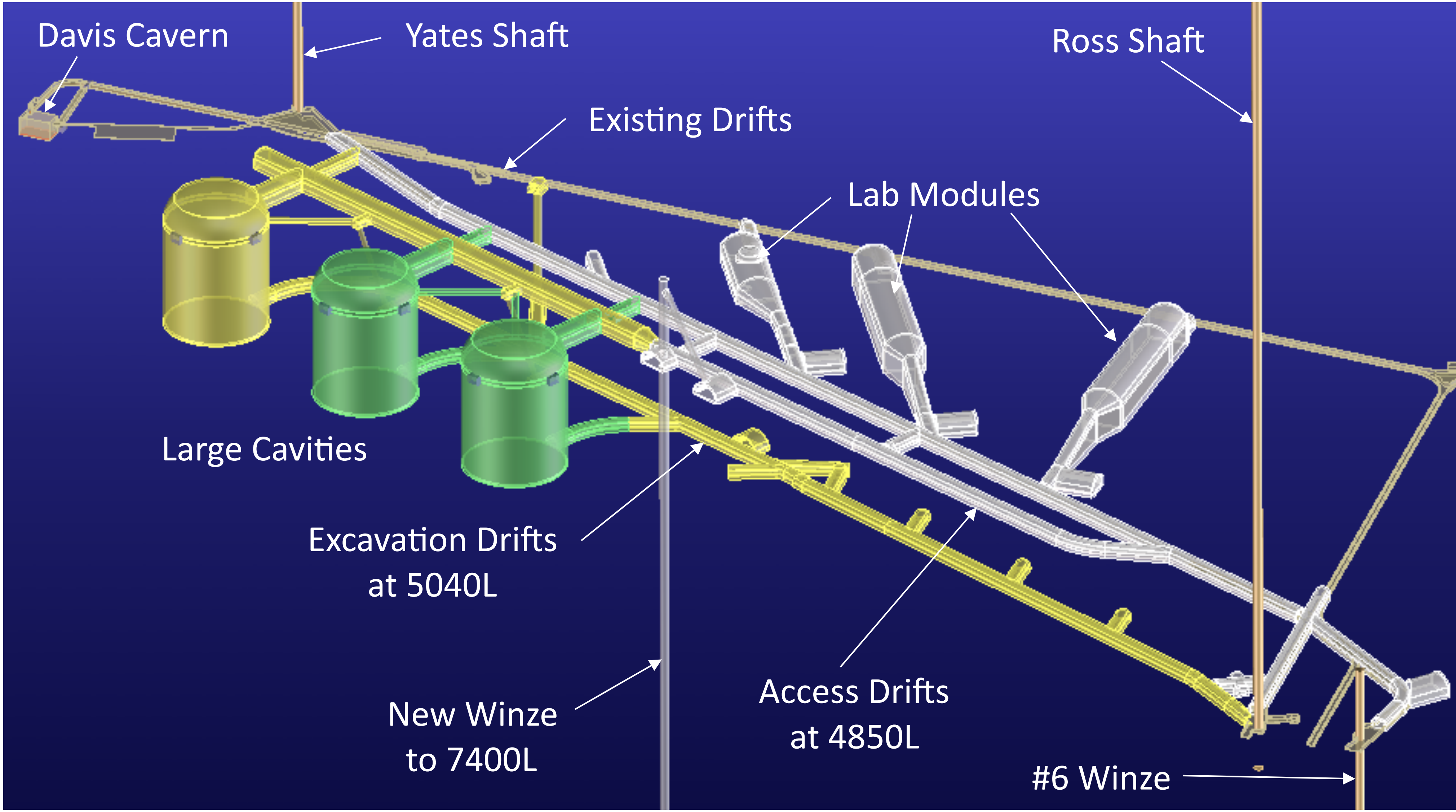
❑ the hierarchy and CP violation: long-baseline neutrinos



- 700 kW beam, on axis, water (or argon) detector, new beamline to DUSEL

- 1300 km of matter: sign of matter effect differs for normal/inverted;

  5 years each of $\nu_\mu \mathrm{s}, \bar{\nu}_\mu \mathrm{s}$ running $\nu_\mu \to \nu_e$ vs $\bar{\nu}_\mu \to \bar{\nu}_e$



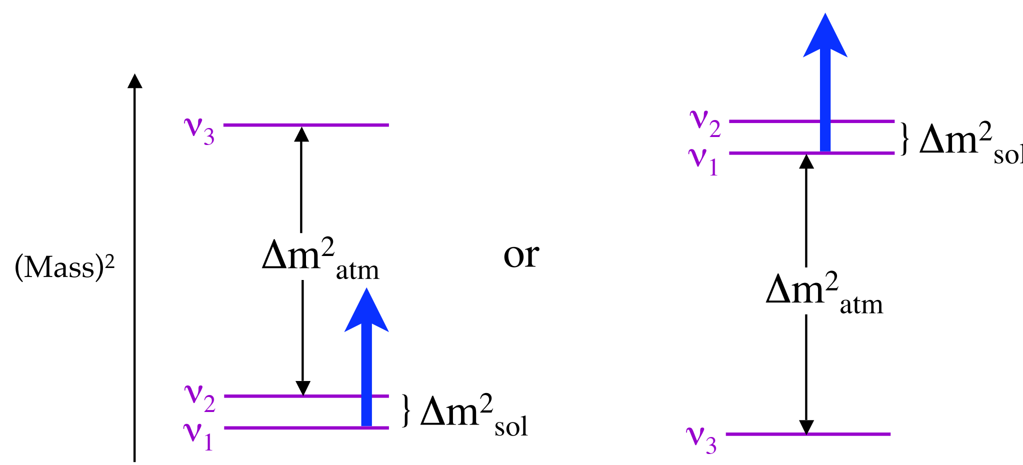
Davis Cavern
Yates Shaft
Ross Shaft
Existing Drifts
Lab Modules
Large Cavities
Excavation Drifts
at 5040L
Access Drifts
at 4850L
New Winze
to 7400L
#6 Winze

Vacuum formula

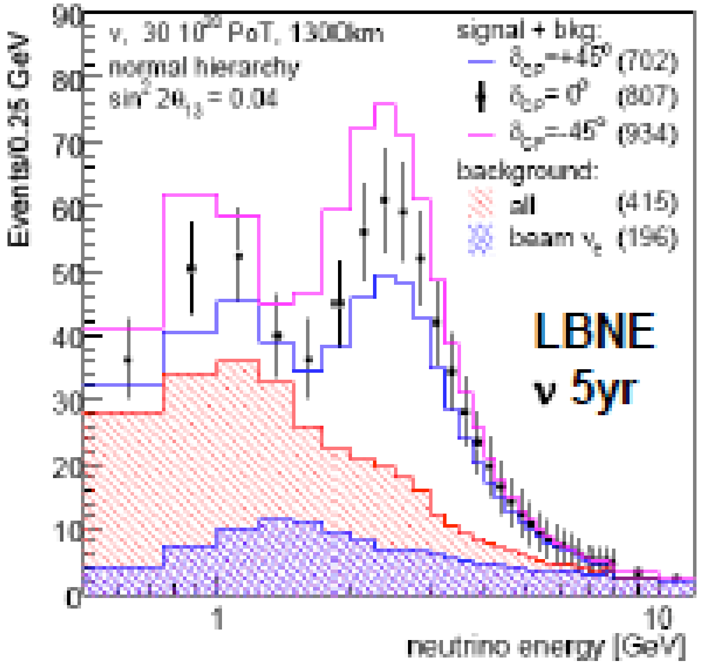
$$P\begin{pmatrix} \nu_\mu \rightarrow \nu_e \\ \bar{\nu}_\mu \rightarrow \bar{\nu}_e \end{pmatrix} = \begin{array}{c} (\sin^2 2\theta_{23} \sin^2 2\theta_{13})(\sin^2 \Delta_{31}) \\ \pm \sin\delta \; (\sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12})(\sin^2 \Delta_{31} \sin \Delta_{21}) \\ + \cos\delta \; (\sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12})(\sin \Delta_{31} \cos \Delta_{31} \sin \Delta_{21}) \\ +(\cos^2 \theta_{23} \sin^2 2\theta_{12})(\sin^2 \Delta_{21}) \end{array}$$

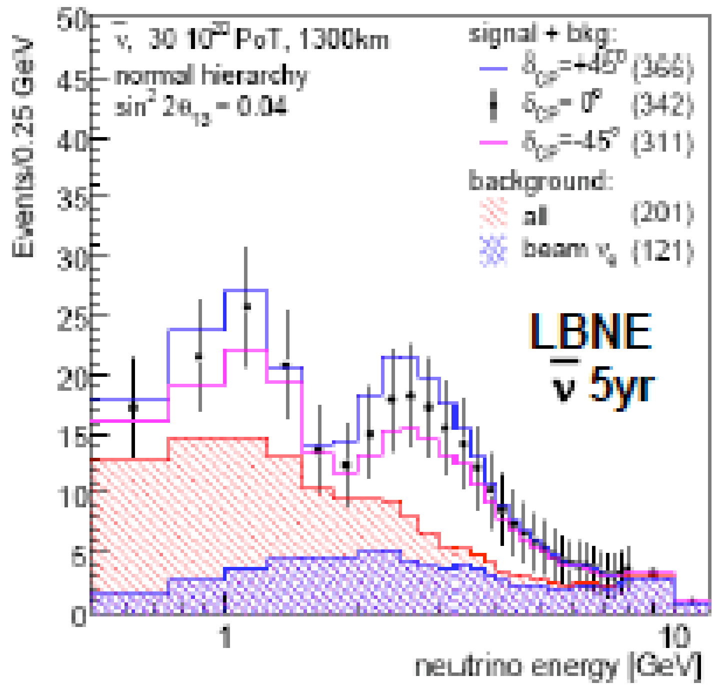
altered by matter

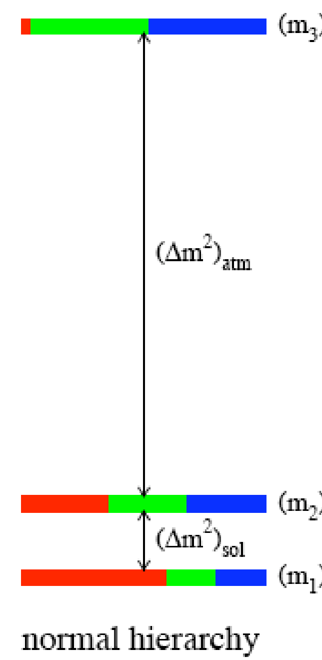
nonzero?



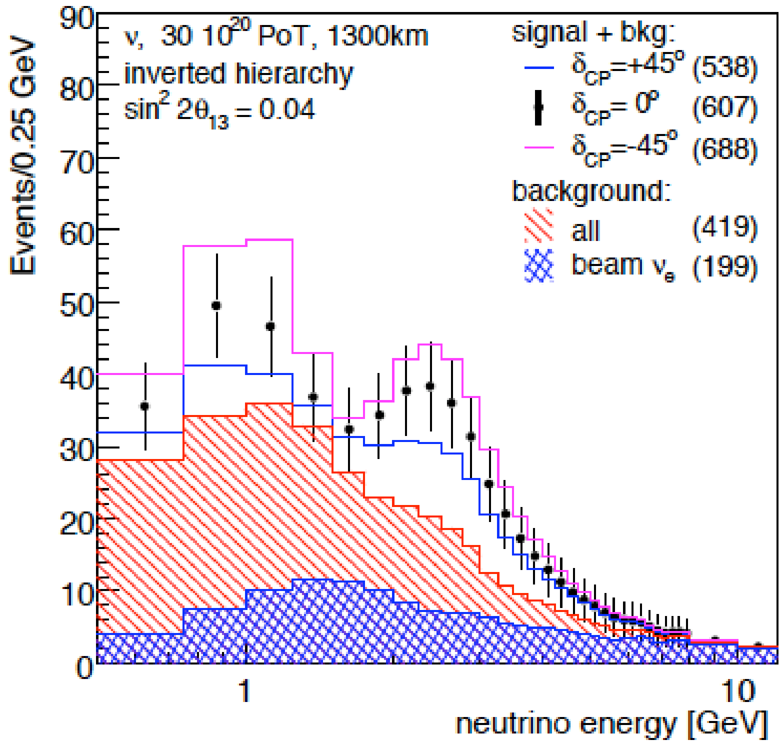
Effects intertwined, as two channels are not CP conjugate when in matter

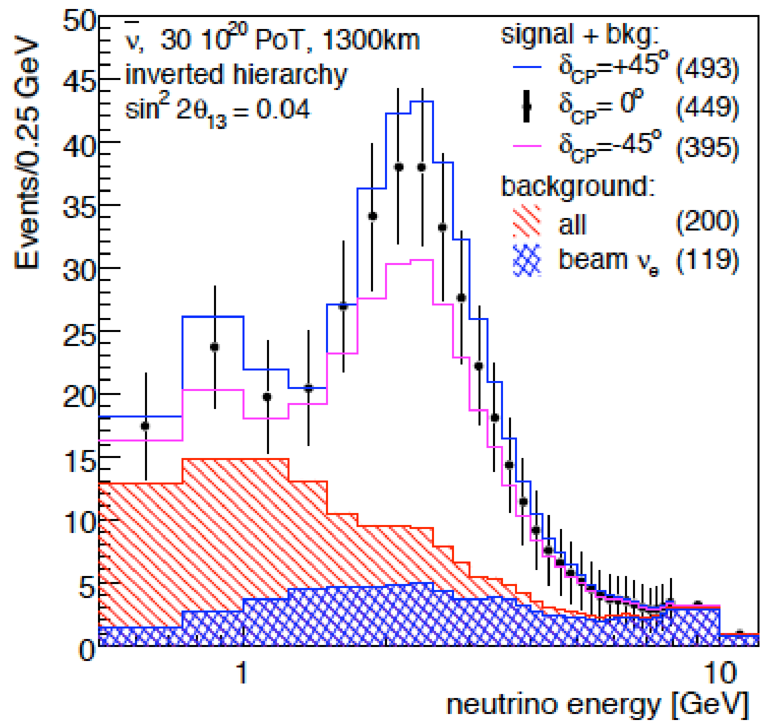


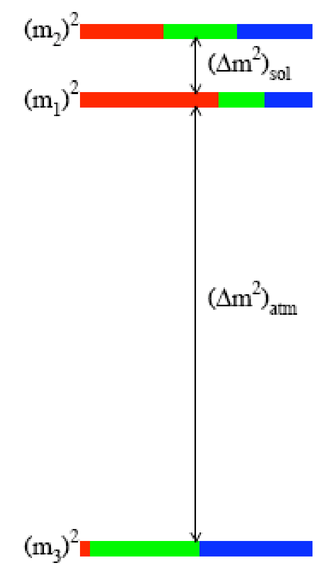




- ❏ broad band beam, centered at about 2 GeV because of baseline
- ❏ low statistics, significant beam contamination, large backgrounds from π^0 production
- ❏ must be able to identify events (quasielastic kinematics) for which one can reconstruct the initial beam energy







inverted hierarchy

- this is a very difficult nuclear physics problem, and many of the event generators are rather naive

- the energy is fixed by the baseline: at 2 GeV, the response is a roughly equal measure of quasi-elastic and resonance production

- produced π^0s escape detection; roughly half of the mesons produced are re-asbsorbed through final-state interactions, with energy lost to unobserved evaporation nucleons; oscillations have altered the beam spectrum from that present in any near detector

- the initial interaction is at high momentum: the tails of the single-nucleon spectral function and scattering off correlated nucleons must dominate the response

- with what certainty can we subtract such events, to isolate the cleaner quasi-elastic signal?

Conclusions

- we were lucky before, and we should hope for luck again:
  - a large absolute mass scale, so that the cosmological signals are significant, and so that $\beta\beta$ decay can confirm
  - large θ_{13} and large δ, so that the LB experiment is as easy as possible

- sometimes one makes his/her own luck
  - nuclear physics should be playing a much larger role in the LB program, particularly in building more realistic analysis tools and validating these at JLab, under similar kinematics
  - we should look for ways to supplement and cross-check the LB experiment: there have been discussions about mounting complementary low-energy experiments with intense stopped-π ν beams -- ideas of this sort will be needed